Inclusive photon production and photon-jet correlations in hadronic collisions

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Abstract

We compare results of k_t-factorization approach and next-to-leading order collinear-factorization approach for photon-jet correlations in pp and $p\bar{p}$ collisions at RHIC, Tevatron and LHC energies. We discuss correlations in azimuthal angle between photon and jet as well as correlations in two-dimensional space of photon and jet transverse momenta. Different unintegrated gluon/parton distributions are used in the k_t-factorization approach. The results depend on UGDF/UPDF used. The collinear NLO $2 \to 3$ contributions dominate over k_t-factorization cross section at small relative azimuthal angles as well as for asymmetric transverse momentum configurations.

1 Introduction

It was realized relatively early that the transverse momenta of initial (before a hard process) partons may play an important role in order to understand the distributions of produced direct photons, especially at small transverse momenta (see e.g. Ref. [1]).

The simplest way to include parton transverse momenta is via Gaussian smearing [1, 2]. This phenomenological approach is not completely justified theoretically.

The unintegrated parton distribution functions (UPDFs) are the basic quantities that take into account explicitly the parton transverse momenta. The UPDFs have been studied recently in the context of different high-energy processes (see [3] and references therein). These works are concentrated mainly on gluon degrees of fredom which play the dominant role in many processes at very high energies. At somewhat lower energies also quark and antiquark degrees of freedom become equally important. Recently the approach which dynamically includes transverse momenta of not only gluons but also of quarks and antiquarks was applied to direct-photon production [4, 5].

Up to now there is no complete agreement how to include evolution effects into the building blocks of the high-energy processes – the unintegrated parton distributions. In Ref. [6] we have discussed in detail a few approaches how to include transverse momenta of the incoming partons in order to calculate distributions of direct photons. In Ref. [7] we have discussed in addition photon-jet correlations.

There is recently at RHIC interest in studying hadron-hadron correlations. The hadron-hadron correlations involve both jet-jet correlations as well as complicated jet structure. Recently preliminary data on photon-hadron azimuthal correlation were presented [8]. In principle, such correlations should be easier for theoretical description as here only one jet enters, at least in leading order pQCD. On the experimental side, such measurements are more difficult due to much reduced statistics compared to the dijet studies.

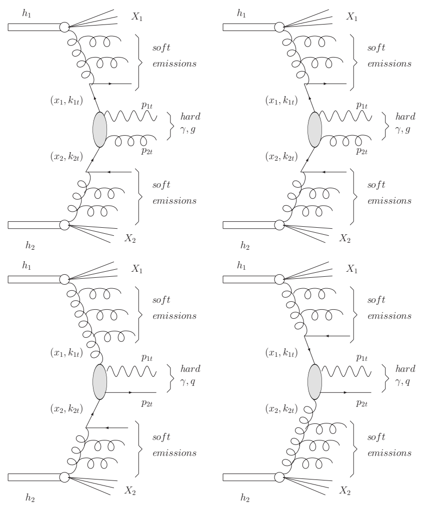

Figure 1: Basic diagrams for the k_t-factorization approach to direct photon correlations production.

2 Formalism

In the k_t-factorization approach the cross section for the production of a pair of photon and parton (γ, l) can be written as

$$\frac{d\sigma(h_1 h_2 \to jet(\gamma) jet)}{d^2 p_{1,t} d^2 p_{2,t}} = \sum_{i,j,l} \int dy_1 dy_2 \frac{d^2 k_{1,t}}{\pi} \frac{d^2 k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}(ij \to \gamma l)|^2} \delta^2(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) \mathcal{F}_i(x_1, k_{1,t}^2) \mathcal{F}_j(x_2, k_{2,t}^2) \; , \tag{1}$$

where

$$x_1 = \frac{m_{1,t}}{\sqrt{s}} \mathrm{e}^{+y_1} + \frac{m_{2,t}}{\sqrt{s}} \mathrm{e}^{+y_2} \; , \tag{2}$$

$$x_2 = \frac{m_{1,t}}{\sqrt{s}} \mathrm{e}^{-y_1} + \frac{m_{2,t}}{\sqrt{s}} \mathrm{e}^{-y_2} \; , \tag{3}$$

and $m_{1,t}$ and $m_{2,t}$ are so-called transverse masses defined as $m_{i,t} = \sqrt{p_{i,t}^2 + m^2}$, where m is the mass of a parton. In the following we shall assume that all partons are massless. The objects denoted by $\mathcal{F}_i(x_1, k_{1,t}^2)$ and $\mathcal{F}_j(x_2, k_{2,t}^2)$ in the equation above are the unintegrated parton distributions in hadron h_1 and h_2, respectively. They are functions of longitudinal momentum fraction and transverse momentum of the incoming (virtual) parton.

In Fig.1 we show basic diagrams included for inclusive photon production and photon-jet correlations in Refs. [6, 7].

The formula (1) allows to study different types of correlations. Here we shall limit to a few examples. The details concerning unintegrated gluon (parton) distributions can be found in original publications (see e.g.[3, 6] and references therein).

3 Results

3.1 Inclusive cross sections

In our analysis we use UPDFs from the literature. There are only two complete sets of UPDFs in the literature which include not only gluon distributions but also distributions of quarks and antiquarks: (a) Kwieciński [9], (b) Kimber-Martin-Ryskin [10]. For comparison we shall include also unintegrated parton distributions obtained from collinear ones by the Gaussian smearing procedure. Such a procedure is often used in the context of inclusive direct photon production [1, 2]. Comparing results obtained with those Gaussian distributions and the results obtained with the Kwieciński distributions with nonperturbative Gaussian form factors will allow to quantify the effect of UPDF evolution as contained in the Kwieciński evolution equations. What is the hard scale for our process? In our case the best candidate for the scale is the photon and/or jet transverse momentum. Since we are interested in rather small transverse momenta the evolution length is not too large and the deviations from initial k_t-distributions (assumed here to be Gaussian) should not be too big.

At high energies one enters into a small-x region, i.e. the region of a specific dynamics of the QCD emissions. In this region only unintegrated distributions of gluons exist in the literature. In our case the dominant contributions come from QCD-Compton *gluon* − *quark* or *quark* − *gluon* initiated hard subprocesses. This means that we need unintegrated distributions of both gluons and quarks/antiquarks. In this case we take such UGDFs from the literature and supplement them by the Gaussian distributions of quarks/antiquarks.

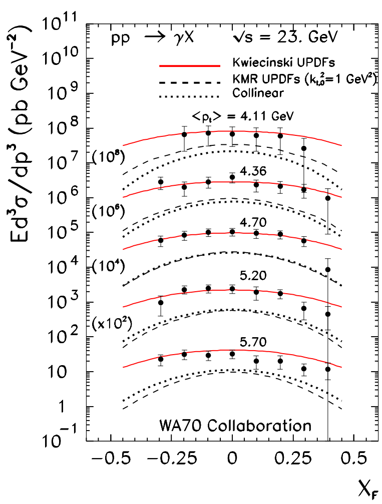

Figure 2: Invariant cross section for direct photons for $\sqrt{s}$ = 23 GeV as a function of Feynman x_F for different bins of transverse momenta. In this calculation off-shell matrix elements for subprocesses with gluons were used. The Kwieciński UPDFs were calculated with the factorization scale μ^2 = 100 GeV^2. The theoretical results are compared with the WA70 collaboration data [12] (right panel).

In Fig. 2 we show as an example inclusive invariant cross section as a function of Feynman x_F for several experimental values of photon transverse momenta as measured by the WA70 collaboration.

It is well known that the collinear approach (dotted line) fails to describe the low transverse momentum data by a sizeable factor of 4 or even more. Also the k_t-factorization result with the KMR UPDFs (dashed line) underestimate the low-energy data. In contrast, the Kwieciński UPDFs (solid line) describe the WA70 collaboration data [12] almost perfect.

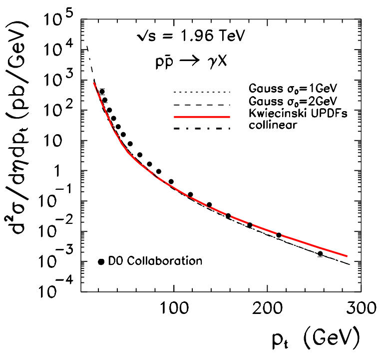

Figure 3: Cross section for direct photons for $\sqrt{s}$ = 1.96 TeV. In this calculation off-shell matrix element for gluons were used. The D0 collaboration data were taken from Ref.[13]. Gaussian smearing (σ_0 = 1,2 GeV) versus Kwieciński UPDFs.

As shown in Ref.[6] the KMR UPDFs strongly overestimate the experimental data at large photon transverse momenta. This is especially visible for proton-antiproton collisions at W = 1.96 TeV when compared with recent Tevatron (run 2) data [13].

In Fig.3 we show an example of theoretical calculations for the Tevatron energy. The Kwieciński UPDFs which seem to converge to the standard collinear result at large photon transverse momenta provide relatively good description of the CDF data.

3.2 Photon-jet correlations

Let us start from presenting our results on the $(p_{1,t}, p_{2,t})$ plane. In Fig.4 we show the maps for different UPDFs used

in the k_t-factorization approach as well as for NLO collinear-factorization approach for $p_{1,t}, p_{2,t} \in (5, 20)$ GeV and at the Tevatron energy $\sqrt{s} = 1960$ GeV. In the case of the Kwieciński distribution we have taken $b_0 = 1$ GeV^{-1} for the exponential nonperturbative form factor and the scale parameter $\mu^2 = 100$ GeV^2. Rather similar distributions are obtained for different UPDFs. The distribution obtained in the NLO approach differs qualitatively from those obtained in the k_t-factorization approach. First of all, one can see a sharp ridge along the diagonal $p_{1,t} = p_{2,t}$. This ridge corresponds to a soft singularity when the unobserved parton has very small transverse momentum $p_{3,t}$. At the same time this corresponds to the azimuthal angle between the photon and the jet being $\phi_- = \pi$. Obviously this is a region which cannot be reliably calculated in collinear pQCD. There are different practical possibilities to exclude this region from the calculations [7].

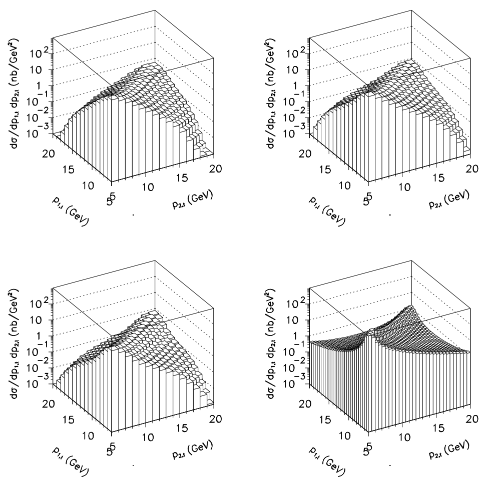

Figure 4: Transverse momentum distributions $d\sigma/dp_{1,t}dp_{2,t}$ at $\sqrt{s} = 1960$ GeV and for different UPDFs in the k_t-factorization approach for Kwieciński ($b_0 = 1$ GeV^{-1}, $\mu^2 = 100$ GeV^2) (upper left), BFKL (upper right), KL (lower left) and NLO 2 $\rightarrow$ 3 collinear-factorization approach (lower right). The integration over rapidities from the interval -5 $< y_1, y_2 <$ 5 is performed.

As discussed in Ref.[6] the Kwieciński distributions are very useful to treat both the nonperturbative (intrinsic nonperturbative transverse momenta) and the perturbative (QCD broadening due to parton emission) effects on the same footing. In Fig.5 we show the effect of the scale evolution of the Kwieciński UPDFs on the azimuthal angle correlations between the photon and the associated jet. We show results for different initial conditions (b_0 = 0.5, 1.0, 2.0 GeV^{-1}). At the initial scale (fixed here as in the original GRV [11] to be $\mu^2 = 0.25$ GeV^2) there is a sizable difference of the results for different b_0. The difference becomes less and less pronounced when the scale increases. At $\mu^2 = 100$ GeV^2 the differences practically disappear. This is due to the fact that the QCD-evolution broadening of the initial parton transverse momentum distribution is much bigger than the typical initial nonperturbative transverse momentum scale.

In Fig.6 we show azimuthal angular correlations for RHIC. In this case integration is made over transverse momenta $p_{1,t}, p_{2,t} \in (5, 20)$ GeV and rapidities $y_1, y_2 \in (-5, 5)$. The standard NLO collinear cross section grows somewhat faster with energy than the k_t-result with unintegrated Kwieciński parton distributions. This is partially due to approximation made in calculation of the off-shell matrix elements [7].

Let us consider now some aspects of the standard NLO approach. In Fig.7 we show angular azimuthal correlations for different interrelations between transverse momenta of outgoing photon and partons: (a) with no constraints on $p_{3,t}$, (b) the case where $p_{2,t} > p_{3,t}$ condition (called leading jet condition in the following) is imposed, (c) $p_{2,t} > p_{3,t}$ and an additional condition $p_{1,t} > p_{3,t}$. The results depend significantly on the scenario chosen as can be seen from the figure. The general pattern is very much the same for dif-

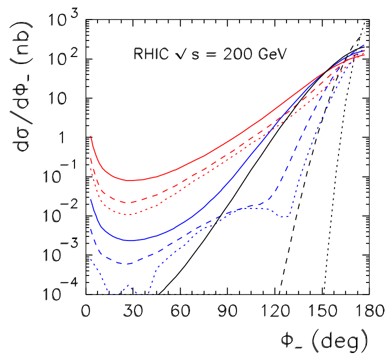

Figure 5: (Color online) Azimuthal angle correlation functions at RHIC energies for different scales and different values of b_0 of the Kwieciński distributions. The solid line is for $b_0 = 0.5$ GeV^{-1}, the dashed line is for $b_0 = 1$ GeV^{-1} and the dotted line is for $b_0 = 2$ GeV^{-1}. Three different values of the scale parameters are shown: $\mu^2 = 0.25$, 10, 100 GeV^2 (the bigger the scale the bigger the decorellation effect, different colors on line). In this calculation $p_{1,t}, p_{2,t} \in$ (5,20) GeV and $y_1, y_2 \in$ (-5,5).

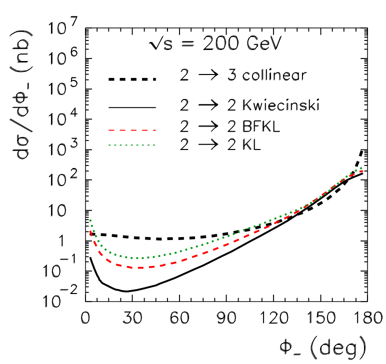

Figure 6: Photon-jet angular azimuthal correlations $d\sigma/d\phi_-$ for proton-(anti)proton collision at $\sqrt{s}$ = 200 GeV for different UPDFs in the k_t-factorization approach for the Kwieciński (solid), BFKL (dashed), KL (dotted) UPDFs/UGDFs and for the NLO collinear-factorization approach (thick dashed). Here $y_1, y_2 \in (-5, 5)$.

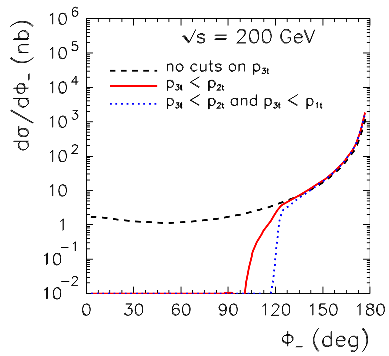

Figure 7: Angular azimuthal correlations for different cuts on the transverse momentum of third (unobserved) parton in the NLO collinear-factorization approach without any extra constraints (dashed), $p_{3,t} < p_{2,t}$ (solid), $p_{3,t} < p_{2,t}$ and $p_{3,t} < p_{1,t}$ in addition (dotted). Here $\sqrt{s}$ = 200 GeV and $y_1, y_2 \in (-5, 5)$.

ferent energies. The figure demonstrates that only higher-order processes contribute to the region of small relative azimuthal angles. We wish to notice that there are no such limitations in the k_t-factorization approach which implicitly include the higher orders.

4 Conclusions

We have discussed both inclusive production of direct photons and photon-jet correlations within the k_t-factorization approach. We have concentrated on the region of small transverse momenta (semi-hard region) where the k_t-factorization approach seems to be the most efficient and theoretically justified tool. In general, the results of the k_t-factorization approach depend on UGDFs/UPDFs used, i.e. on approximation and assumptions made in their derivation.

We have obtained very good description of the world data for the photon single particle distributions with the Kwieciński UPDFs.

An interesting observation has been made

for azimuthal angle correlations. At relatively small transverse momenta ($p_t \sim$ 5–10 GeV) the $2 \to 2$ subprocesses, not contributing to the correlation function in the collinear approach, dominate over $2 \to 3$ components. The latter dominate only at larger transverse momenta, i.e. in the traditional jet region. We have calculated correlation observables for different unintegrated parton distributions from the literature.

We have discussed the role of the evolution scale of the Kwieciński UPDFs on the azimuthal correlations. In general, the bigger the scale the bigger decorrelation in azimuth is observed. When the scale $\mu^2 \sim p_t^2$(photon) $\sim p_t^2$(associated jet) (for the kinematics chosen $\mu^2 \sim 100$ GeV^2) is assumed, much bigger decorrelations can be observed than from the standard Gaussian smearing prescription often used in phenomenological studies.

The correlation function depends strongly on whether it is the correlation of the photon and any jet or the correlation of the photon and the leading-jet which is considered. In the last case there are regions in azimuth and/or in the two-dimensional $(p_{1,t}, p_{2,t})$ space which cannot be populated in the standard next-to-leading order approach. In the latter case the k_t-factorization seems to be a useful and efficient tool.

At RHIC one can measure jet-hadron correlations only for not too high transverse momenta of the trigger photon and of the associated hadron. This is precisely the semihard region discussed here. In this case the theoretical calculations would require inclusion of the fragmentation process. This can be done easily assuming independent parton fragmentation method.

5 Acknowledgments

Antoni Szczurek is indebted to Frederic Kapusta and his colleagues for nice atmosphere during the conference.

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